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Developing Racing Exhaust System Performance using Computational Fluid Dynamics Software

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Abstract. The exhaust system is one of the most important parts for internal combustion engine-powered car, serve as the only device which supports the exhaust process to dispose the combustion residue from combustion chamber caused by the combustion process. Exhaust system design can affect the entire engine performance and efficiency so its very crucial when it comes into designing the exhaust system and it is important to understand how to design a suitable exhaust system for certain engine when it comes to racing purpose or motorsports. In motorsports, a well design exhaust system proved in increasing the engine efficiency which means higher engine efficiency creates more power output which is needed in the world of motorsports to increase the probability of winning. When it comes into exhaust tuning, the width diameter and length of the exhaust system proved to affect the torque of the engine and its very crucial to tune the torque performance to suit the engine characteristics so the engine can perform in optimal performance and higher efficiency. For motorsports, its not only concerned about how much power that can be produces from the engine, but also about the durability of the engine because higher power output produces more heat and combustion residue due to high piston and crankshaft revolution which means the combustion residue in the combustion chamber needed to be emptied quickly to the exhaust system for the next combustion process. In this research, it will be explained how to design a 3D racing exhaust system based on CAD software and obtain the fluid velocity data based on computational fluid dynamics (CFD) software. In future, this method will be useful for car manufacturers to develop a suitable exhaust system for a lower cost.

Keywords: Computational Fluid Dynamics, Scavenging Effect, Flow Rate, Backpressure, Meshing

INTRODUCTION

The world of racing/motorsports is a sport that combines man and machine at a fast-paced racing on a racetrack. Many people's still consider that motorsports are only a means of damaging the environment, wasting large amounts of time and money, that is why this sport is glimpsed by the world community, it is the same case happened in Indonesia.

Motorsports is an unofficial engineering and science research in automotive world which has the main goal of winning the race. Evidence that motorsports is a research experiment are from the many automotive technologies that are derived from race car technology to street-legal cars such as Anti-lock Braking System (ABS), Traction Control System (TCS), Active Steering Management (ASM), Electronic Brake Distribution (EBD), catalytic converters, hybrid systems, Kinetic Energy Recovery Systems (KERS), active suspension to active aerodynamic which is a derivative of technology from Formula 1, Le Mans 24 Hours, Touring Car Championships, Rally, and Moto GP. Although research in the field of motorsports is oriented to winning the race, but to create continuity in terms of business, after these technologies are used and tested for performance on the racetrack, these technologies are sold

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and installed on street-legal cars in order to improve performance, energy efficiency, comfort, convenience and safety, in other words, racing is a proving ground of newly developed automotive technology. One of the researches in the field of motorsports that aims to improve the efficiency of engine performance in order to obtain higher overall car performance is research on vehicle exhaust or specifically called exhaust systems. Exhaust system not only acts as a flue or chimney for residual emission gases, if its designed correctly it can improve engine the overall performance and efficiency nearly 20%, the increased of engine efficiency will also have an impact to the combustion chamber which can be more cleaner and clean combustion chamber produces cleaner exhaust gas emissions. The process of making a proper exhaust system involves many fundamental theories of existing physical laws. Theories involved include shear stress theory and other material science theories, Navier Stokes theory that describes the conservation of mass and energy, heat transfer theory, aerodynamic and the easiest is Bernoulli's theory.

The theories of physics are considered still not capable in assisting engineers in designing a suitable exhaust system, because each car has engine characteristics, volumetric efficiency and different exhaust Cubic Foot per Minute (CFM) discharges, so as to cover these shortcomings the engineers use a research-based approach computer simulation is Computational Fluid Dynamic (CFD) to analyze the character of the combustion flue gas that passes through a vehicle's exhaust system. The complexity in designing the right exhaust system is not over, the difference in the dimensions of the exhaust pipe both the width and length difference will also affect the fluid pressure in the exhaust which leads to differences in the performance of the resulting exhaust gas and the selection of the right material for the exhaust, so this complexity. This addition can be referred to as exhaust tuning in the world of motorsports.

Exhaust system does not have the best and worst benchmarks, exhaust system for every single car and engine has their uniqueness because exhaust system design depends on the exhaust flow rate from the exhaust manifold and the overall geometry size of the car. However, there are some of exhaust tuning theory by changing the size of the exhaust pipe width diameter, for the power-oriented exhaust system, the design process will be different from the conventional eco-friendly and low noise exhaust system. So in the end, it is necessary to hold an experimental test to prove the exhaust system that is made can produce a performance which satisfies the requirement, but the cost for conducting the experimental test is very high. Then CFD is here to answer the high-cost problem from conducting experimental test, in other words by changing the experimental test into simulation test based on CFD. It can still produce highly accurate results data which nearly 95% accurate to the experimental results data if the CFD process is done with the correct procedure. For the best experimental test that is still affordable to test the performance of the exhaust system made is the Honda Brio Speed Challenge that is on the Indonesia Sentul Series of Motorsports calendar [1].

METHODS

There are two types of the exhaust system, the first one is normal exhaust system which includes catalytic converter, resonator and muffler, the second one is straight pipe exhaust system which not includes those 3 components like in normal exhaust system. This research focused on the exhaust system for Honda Brio Satya owned by EnginePlus Motorsports and firstly conducted at round 3 of Indonesia Sentul Series of Motorsports and this research had 2 phase of research such as pre-research and research phase.

Pre-Research

Direct observation to Sentul International Circuit to see the performance of the Honda Brio Satya 2019 owned by EnginePlus Motorsports, learn the behavior of the car on race track by supervise the lap time of every single lap, analyze the performance of EnginePlus Motorsports Honda Brio Satya during the qualifying and race session by looking at the lap time data provided by Sentul Circuit. We create initial hypotheses based on direct observations and data obtained and then conduct an examination for Honda Brio Satya condition after the race at the Sentul Circuit.

Research Phase

Measuring the exhaust head of the Honda Brio Satya engine block, this is done so that the original size can be used as a reference in the process of drawing 3D exhaust head pipe owned by Honda Brio Satya.

FIGURE 1. (a) Exhaust port for L12B engine located on the engine block, (b) Measuring the diameter of the exhaust port, (c) Engine block of L12B engine

Study the geometry of the Honda Brio Satya exhaust system for 3D image processing in a 3D design software application so that the 3D image approaches its original shape. Drawing the straight exhaust pipes that vary in length between 500 mm to 1500 mm, and vary in diameter between 1.5" to 1.75". We combined the results of the above variations into 1 form of the 3D version of the exhaust system and find the amount of flow of exhaust gases from the exhaust head with the flow bench engine and flow bench calculator in CFM units. Carrying out the 3D model design process with Solidworks software, this 3D model is needed to obtain the digital version of the geometry of the exhaust system so that it can be simulated with computational fluid dynamic software.

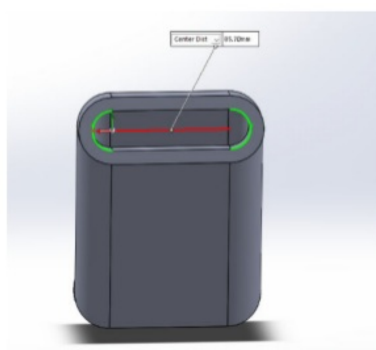

FIGURE 2. 3D model of exhaust head port

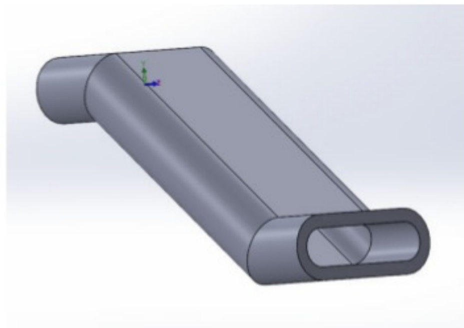

FIGURE 3. 3D model of the exhaust head from downpipe (exhaust manifold), with a diameter of 85.7 mm according to the original size measured on the Honda Brio L12B engine block.

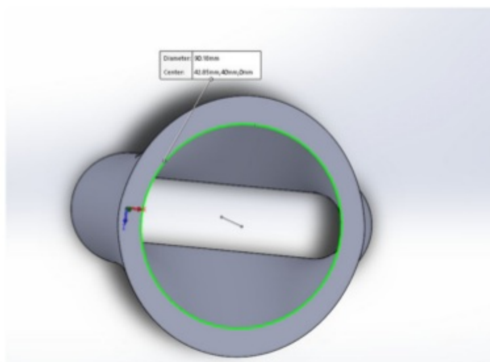

FIGURE 4. Sphere to round joint, following the original shape of the Honda Brio exhaust system with a diameter of 90.18 mm

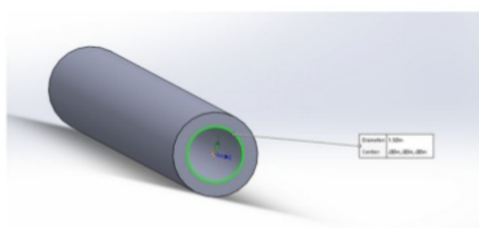

FIGURE 5. Section exhaust pipe with a diameter of 1.5 inch

According to Figure 5, that straight pipe part of the entire exhaust system is the main research. This research will try to creates different diameter for the exhaust pipe parts.

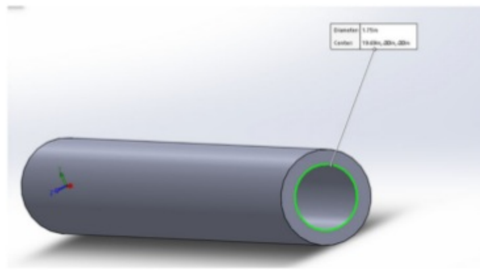

FIGURE 6. Section exhaust pipe with a diameter of 1.75 inches

Based on Figure 6, the variations in the diameter of the exhaust pipe are made from 1.5 inches, 1.75 inches and 2 inches because the difference in the diameter of the exhaust pipe results in differences in the characteristics of the exhaust gas fluid which results in differences in the performance of the exhaust system [2].

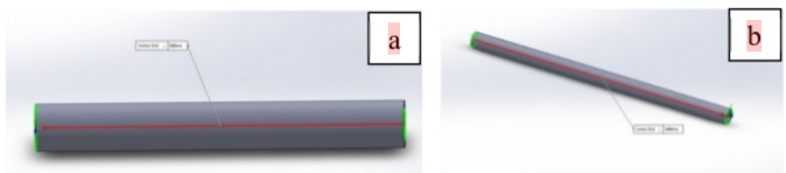

FIGURE 7. Two different lengths for straight pipe exhaust part (a) 500 mm to (b) 1,000 mm respectively

The length of the exhaust pipe is also varied from 500 mm, 1,000 mm, up to 1,500 mm. The difference in exhaust pipe lengths results in differences in the character of the exhaust gas fluid, thus affecting the overall exhaust performance and affecting the performance of the car [3].

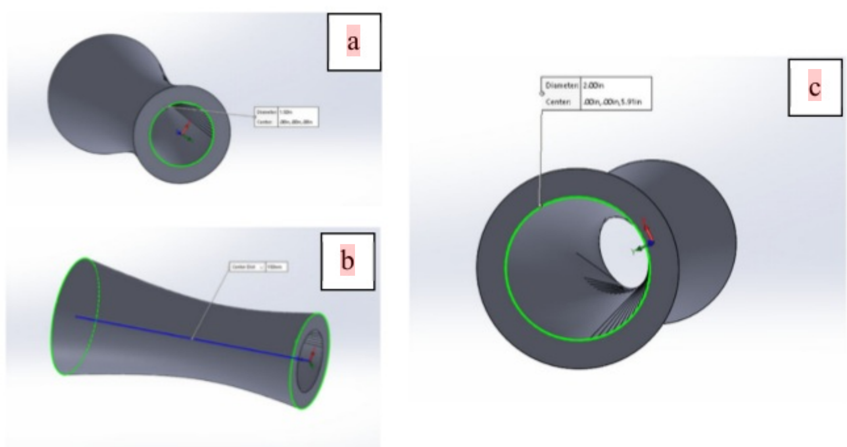

FIGURE 8. At the tip of the exhaust (exhaust tip), vary with Megaphone (a) the front faces of the megaphone exhaust pipe in 1.5-inch diameter, (b) the length of the megaphone exhaust pipe in 150 mm, (c) the rear faces of the megaphone exhaust pipe in 2-inch diameter

Megaphone serves to equalize the pressure from inside and outside the exhaust so that the effect of backpressure that inhibits the flow of exhaust fluid to be discharged into the air is minimized [4]. Backpressure has a terrible impact on exhaust performance and could damage the exhaust system which led to break caused by the failure of an engine heat pulse to be disposed of by the exhaust system [5].

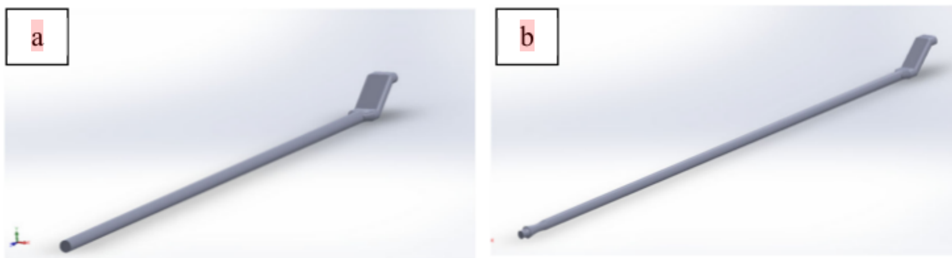

FIGURE 9. Difference design at the tip of the exhaust for the megaphone exhaust system (a) a straight pipe exhaust and (b) a megaphone exhaust

Figure 9 shows the 3D results of the exhaust system made by CAD software, the first exhaust system is a straight pipe exhaust and the second exhaust system is a megaphone exhaust. Both exhaust systems have different characteristics of the exhaust gas fluid so that the performance between the two is different and it indirectly stated the main idea of this research which is to creates many different types of straight pipe exhaust system for racing purpose by varying the configuration arrangement and width diameter. The overall length of the exhaust system that has varied in diameter and the length of the pipe is constant for 3000 mm, after finished create 12 different exhaust system configuration based on different pipe diameter and length, the research continues by conducting fluid flow simulations with CFD software to obtain fluid velocity data from the flow of the fluid (emission gases) that flew inside the exhaust system. Based on data from fluid velocity on the exhaust system, several hypotheses could be made including vibration and backpressure effect.[6].

RESULTS AND DISCUSSION

After the 3D design process, CFD is used to obtain the overall data performance for each exhaust system. Firstly it is required to know the flowrate from the exhaust head of the L12B engine which is usually on CFM unit, then convert the CFM unit into fluid velocity unit (m/s). According to the database of L12B engine it has of displacement 1198 cc, with bore 73 mm (2.82 in.) and stroke 71.58 mm (2.87 in.), with compression ratio 10.2 : 1, power 90 ps @ 6200 RPM, peak torque 114 Nm @ 4900 RPM. CFM calculator is used by inputting displacement, max power RPM and volumetric efficiency 90%, we get result 105 CFM_ or 6.11 m/s.

To determine the fluid characteristics, whether it is laminar or turbulent, first it needs to calculate the Reynold Number. The formula of the Reynold Number is $Re = \frac{\rho.V.L}{\mu}$ and the Re results from the calculation is 1.222.000. If the Re is more than 2300 for internal flow, Then it categorized as turbulent flow by using the CFD, we can determine the fluid flow velocity. The 6.11 m/s used as initial inlet fluid velocity that came from the exhaust port to the exhaust system.

Based on requirement for racing, firstly CFM is cubic feet per minute, in other words, it is a unit of flow discharge, on internal combustion engine which to produce power needs air, fuel and fire, we can conclude that more air means producing more power, so for racing purposes, it is concerned that searching for which exhaust system can produce high value of CFM. But the simple Bernoulli's theory involved in this research, it is known that high fluid velocity creates low pressure and low fluid velocity creates high pressure, based on Bernoulli's theory too that fluid travelled from high-pressure state into low-pressure state, this theory has a relation with backpressure phenomena which is terrible effect for the engine and the entire car performance will be reduced. From that theory we can conclude that higher value of CFM exhaust system creates high fluid velocity and low pressure and lower value of CFM exhaust system creates low fluid velocity and higher pressure so in other words the higher value of CFM not always a good result. The exhaust system also affecting the scavenging effect, scavenging effect is a suction effect created by the difference in pressure of two different places and diameters [7, 8].

How the scavenging effect works :

1. Works after the piston reach Top Dead Center (TDC).
2. When the exhaust valve opened, the residual gas is being sucked by the exhaust pipe. This happens because the exhaust pipe is in vacuum condition.
3. When the car being ignite, the low pressure initially created when the first exhaust fluid flowing through the exhaust system.
4. Smaller diameter pipe can increase the fluid velocity which lowering the pressure and increasing the scavenging effect power.
5. The more the gas residual being sucked by the exhaust downpipe, the more the free room in the combustion chamber to be filled by the new fresh air and gasoline mixture which can increase the efficiency of the engine.
6. Higher engine efficiency means the engine can produce higher power.
7. Same as the engine, the standard exhaust also have the ideal work temperature is around 400 ^{0}C – 700 ^{0}C.

TABLE 1. Basic exhaust system sample with total of 3 meters of overall length

Sample	Diameter Configuration (inch)			Average Velocity (m/s)
Sample A	1.50	1.50	1.50	15.43 m/s
Sample B	1.50	1.50	1.75	14.90 m/s
Sample C	1.50	1.75	1.50	14.86 m/s
Sample D	1.75	1.50	1.75	14.56 m/s
Sample E	1.75	1.75	1.50	14.57 m/s
Sample F	1.75	1.75	1.75	12.79 m/s

TABLE 2. Special Exhaust System with Joint Smoothing, different Pipe Length at Certain Part, and Megaphone with Total 3 Meters of Overall Length

Sample Special	Diameter Configuration (inch)			Average Velocity (m/s)
Sample Special A	1.50	1.50	1.75	14.85 m/s
Sample Special B	1.75	1.50	1.75	14.52 m/s
Sample Special C	1.50	1.75	1.50	14.30 m/s
Sample Special D	1..50	1.50	2.00	13.45 m/s
Sample Special E	1.50	1.50	1.75	14.17 m/s
Sample Special F	1.50	1.75	2.00	15.49 m/s

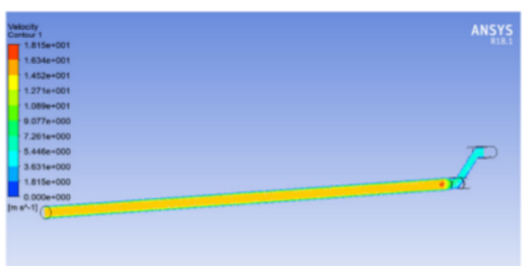

FIGURE 10. Sample A

Figure 10 shows fast and uniform fluid flow from inlet into outlet of the exhaust, medium to high chance of backpressure potential.

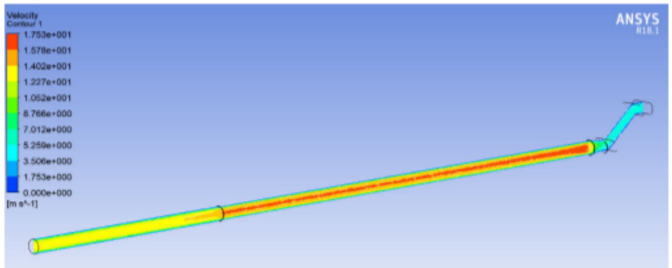

FIGURE 11. Sample B

The 1.75-inch exhaust pipe slowing down the fluid flow but reducing the chance of backpressure which also good for exhaust process even with a lower value of CFM.

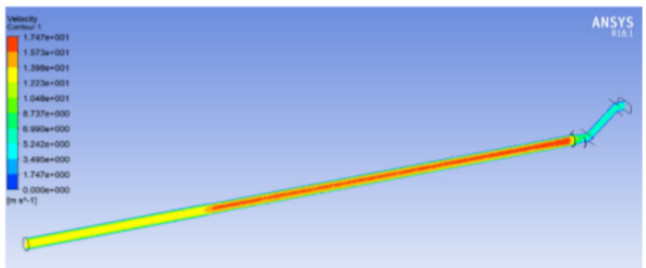

FIGURE 12. Sample Special A

Joint smoothing is the smoother design for the transition from 1.5 inches into 1.75 inches which expected to affect the fluid flow. With joint smoothing, uniform fluid flow characteristics on first 2 m and being accelerated due to small diameter, joint smoothing mods are created to make the flow transition from 1.5 to 1.75 smoother, also reducing shear stress on exhaust wall by lowering the flow velocity.

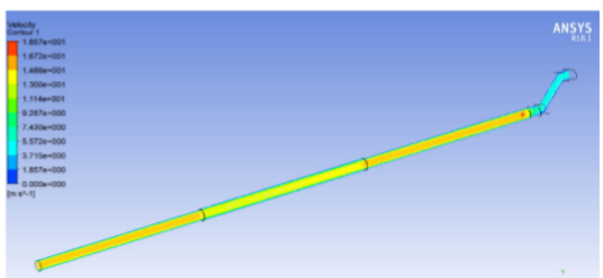

FIGURE 13. Sample C

Fluid flow on this exhaust has been reduced significantly by the 1.75-inch pipe, the 1.75-inch pipe act as a resonator to resonate the sound of the engine to make it more silenced and stabilizing the decibel and mechanical vibration.

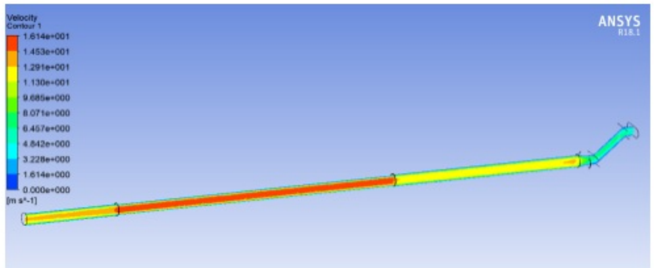

FIGURE 14. Sample Special B

Even 1.75-inch pipe as exhaust tip, but small dimension makes this exhaust got high outlet fluid flow velocity, not only small diameter but also the 1.5 inches 1.5 m at the center of the exhaust accelerating the fluid flow, makes the fluid flow faster at the middle pipe of the exhaust.

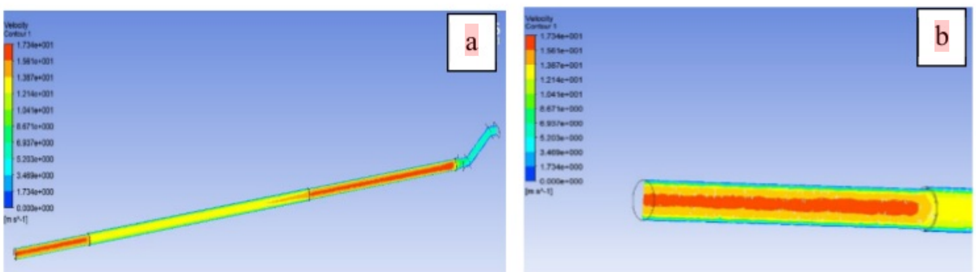

FIGURE 15. Sample Special C (a) 1.5 inch 1 meter – 1.75 inches 1.5 meter – 1.5 inches 0.5 meter total 3 meters of overall length, (b) the velocity at the exhaust tip at a 1.5-inch pipe

In Figure 15 (a), theory supposed to make the engine sound more silence, lowering the mechanical vibration and stabilizing the sound decibel, but this type of exhaust not suitable for racing.

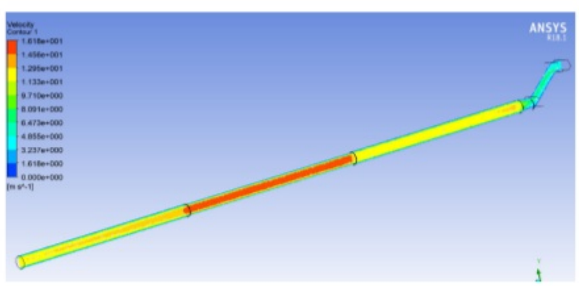

FIGURE 16. Sample D

Decreasing the pipe diameter in the middle of the exhaust does not give good result.

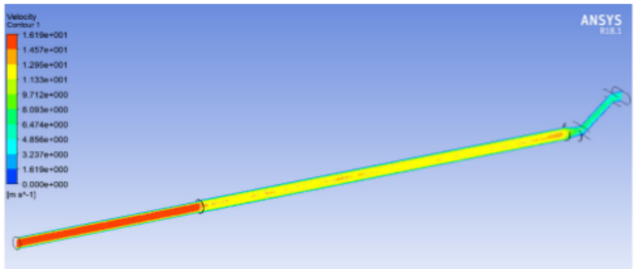

FIGURE 17. Sample E

In sample E, big diameter exhaust pipe as the first part of exhaust configuration slowing down the exhaust fluid velocity and even the third part of the exhaust has a smaller diameter, but it still failed to increase overall fluid velocity of the entire exhaust.

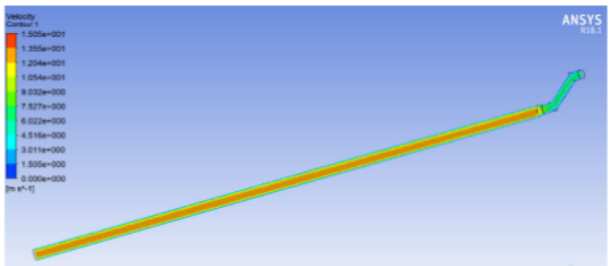

FIGURE 18. Sample F

Figure 18 shows uniform fluid flow with slow fluid velocity and low pressure of the exhaust system.

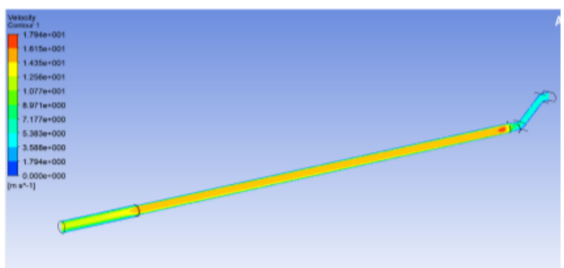

FIGURE 19. Sample Special D

From 1.5 inch into 2 inch makes the fluid flow velocity has been decreased significantly at the end of the exhaust, which is lowering the chance of backpressure.

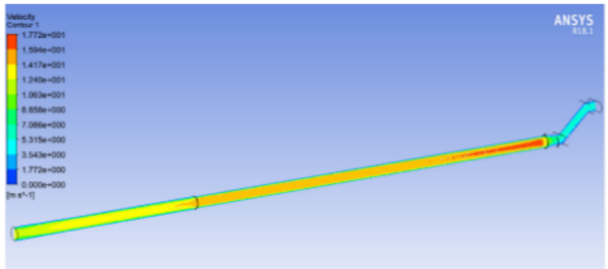

FIGURE 20. Sample Special E

The 1.5-1.5-1.75 megaphone exhaust total 3 meters of overall length Suitable for daily use but racing still need some research. The main function is adjusting pressure between exhaust pressure and atmospheric pressure to reduce the chance of backpressure. 17.72 m/s + 15.94 m/s + 14.17 m/s + 12.4 m/s 10.63 m/s : 5 = 14.172 m/s → 243.45 CFM.

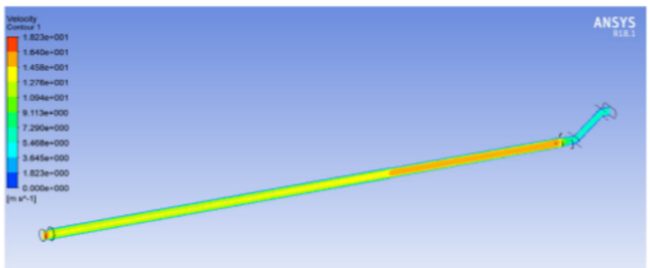

FIGURE 21. Sample Special F

The 1.75 inch mid-pipe is for lowering the fluid velocity but makes the car has better torque in higher RPM, with 2 inch megaphone at the tip of the exhaust to equalize the pressure inside the exhaust system with the pressure at the atmosphere.

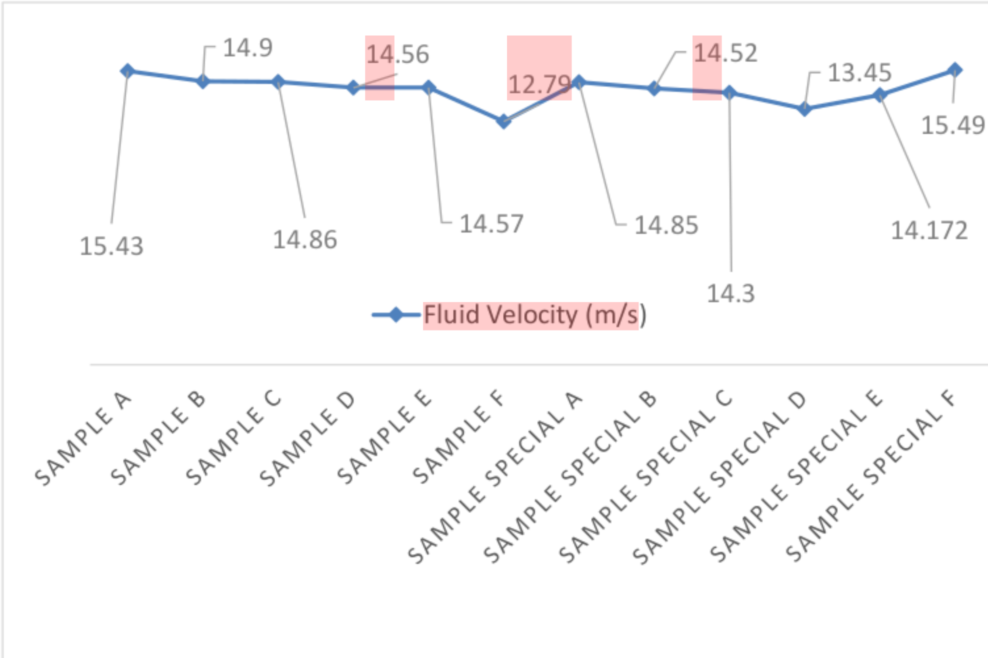

FIGURE 22. CFM comparison graph, the X-axis shows the exhaust type and the Y-axis is the CFM value

It can be seen that Sample A and Sample Special F have the highest fluid flow velocity with low fluid pressure which are suitable for racing purposes but had high chance of backpressure, it doesn't mean that the low fluid velocity is terrible, because low fluid velocity has higher pressure on the exhaust system which has lower chance of backpressure.

CONCLUSION

The last megaphone exhaust have the highest fluid velocity among others exhaust design, The velocity contour represented by the CFD simulation also describe the exhaust fluid flow, exhausts with more uniform velocity contour have less mechanical vibration and fluid stability which can affect the durability and performance of the exhaust to be more durable, megaphone and wide diameter pipe at the end of the exhaust has less chance of backpressure and for small diameter exhaust is vice versa. Race car usually used straight pipe exhaust system with small width diameter because straight pipe exhaust provide free flow condition which can dispose the emissions (including exhaust gases and heat pulse as combustion residual) faster than normal exhaust system which can increase the power of scavenging effect, but in racing condition because the engine is always in high RPM, the backpressure effect can be neglected due to high speed constant fluid flow from the engine through the exhaust system and of course race car doesn't through stop and go condition for too long which if it does it would be dangerous for the engine because the backpressure effect is powerful for straight pipe exhaust system. If a straight pipe exhaust system are implemented on daily used cars, then it will not suitable and can create an amount of backpressure because the atmospheric fluid is sucked by the straight pipe exhaust when the car is in idle condition, the sucked fluid inhibit the exhaust fluid process which can make it hard or even fail to be disposed to the atmosphere. The side effect from this occurring is the heat pulse residue from combustion chamber are failed to be disposed and the heat pulse will still be inside the exhaust system which can damage the exhaust system or in a worst-case scenario, it will damage the engine. The backpressure effect on straight pipe can be neglected if the engine always in high RPM condition (racing) which can creates high value of fluid velocity, even we assume there is amount of backpressure exists as a hindrance at the tip of straight pipe exhaust, the high value of fluid velocity still can push through the backpressure and still can dispose the emission gases properly. Is not always mean that higher fluid velocity can produce more horsepower even bigger scavenging effects means more air injected to the combustion chamber which can increase engine efficiency and performance, to confirm if an exhaust system can increase horsepower, it still needs to be validated by dyno run test. The use of diffuser and megaphone application is to reduce the value of initial backpressure for example from 2G into 1G or 0.5G by reducing the fluid velocity, but the reduces of fluid velocity doesn't mean that the horsepower of the engine reduced, it still needs to be confirmed with dyno run test for better results, to solve backpressure problem for the straight pipe exhaust, then megaphone is attached at the tip of the exhaust and theoretically can reduce backpressure, but to be sure for increasing performance, it must be tested in dyno run to confirm and validate the CFD simulation test to discover which exhaust system design can produce higher and higher horsepower.

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